The case for Ultra-Light Boson Dark Matter

Asimina Arvanitaki
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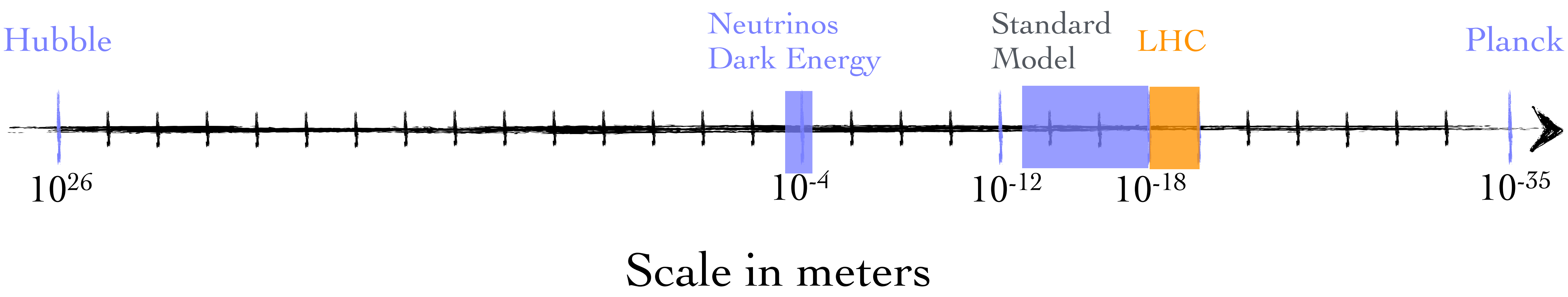
The High Energy Frontier

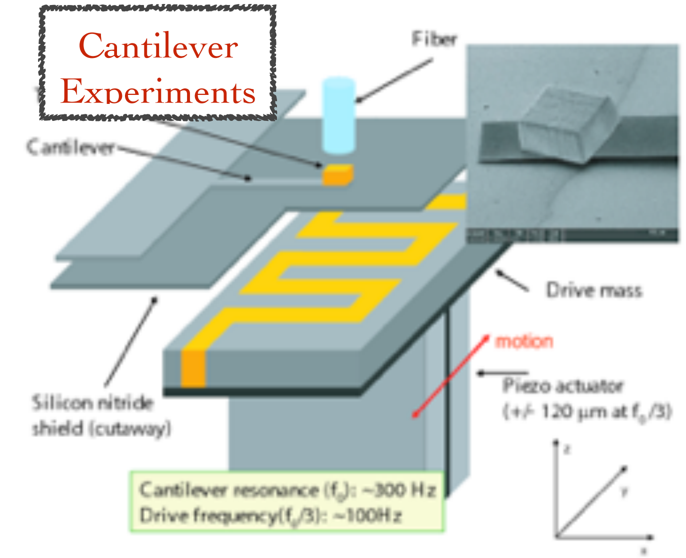
Particle Physics — Precision vs Energy Frontier



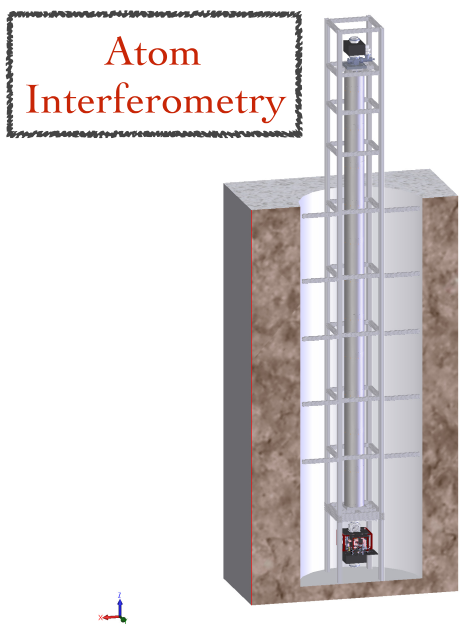
80% of scales unexplored

Opportunities to probe the low energy frontier

- Short Distance Tests of Gravity
- Extra Dimensions



Dimopoulos, Kapitulnik (1997)

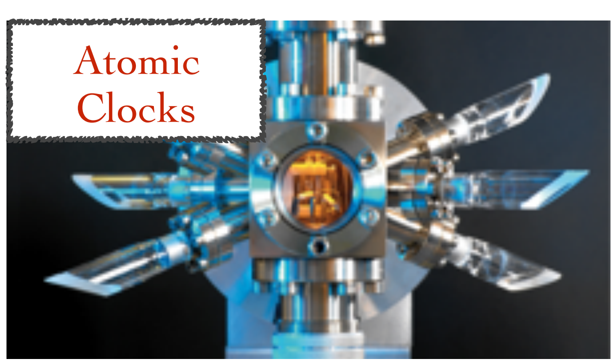


- Tests of Gravity
- Gravitational Wave detection at low frequencies
- Tests of Atom Neutrality at 30 decimals

Dimopoulos, Geraci (2003)
Dimopoulos, Kasevich et. al.(2006-2008)

- Axion Dark Matter Detection
- Axion Force Detection

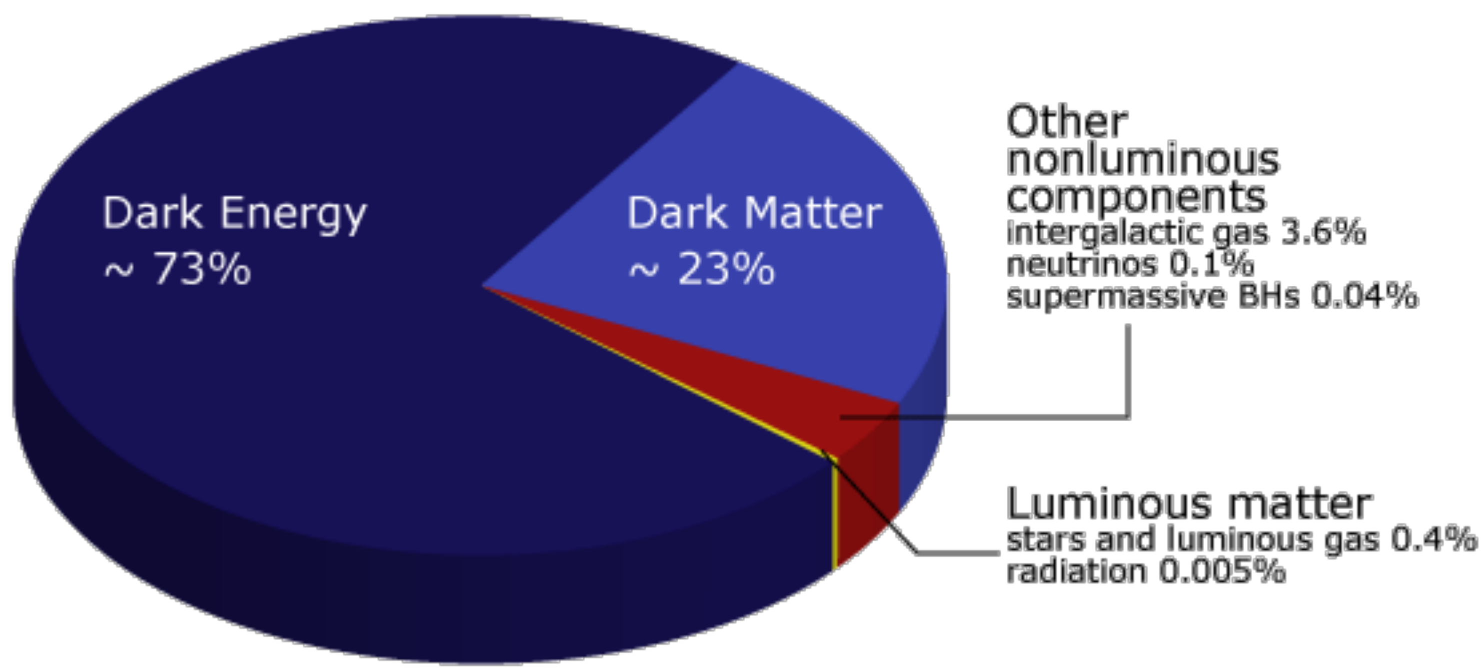
Graham et. al. (2012)
AA, Geraci (2014)



- Setting the Time Standard
- Dilaton Dark Matter Detection

AA, Huang, Van Tilburg (2014)

The Mystery of Dark Matter

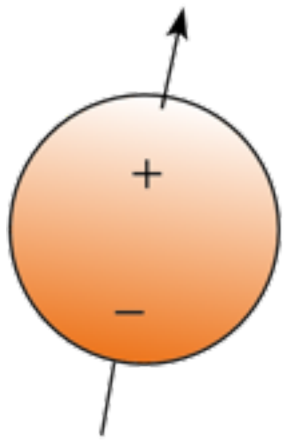


Models of Dark Matter

- What is it made out of?
- How is it produced?
- Does it have interactions other than gravitational?

Why is the Electric Dipole Moment of the Neutron Small?

The Strong CP Problem and the QCD axion



Neutron Electric Dipole Moment
$\sim$ e fm θ_{QCD}

$$L_{\rm SM} \supset \frac{g_s^2}{32\pi^2}\theta_{\rm QCD} G^a \tilde{G}^a$$

Experimental bound: $\theta_{QCD} < 10^{-10}$

Solution:
θ_{QCD} is a dynamical field, an axion

Weinberg(1978) and Wilczek (1978)
Peccei and Quinn (1977)

Axion mass from QCD:

$$\mu_a \sim 6 \times 10^{-11}\ \mathrm{eV}\ \frac{10^{17}\ \mathrm{GeV}}{f_a} \sim (3\ \mathrm{km})^{-1}\ \frac{10^{17}\ \mathrm{GeV}}{\mathrm{f_a}}$$

$\mathrm{f_a}$: axion decay constant

Elements of String Theory

- Extra dimensions

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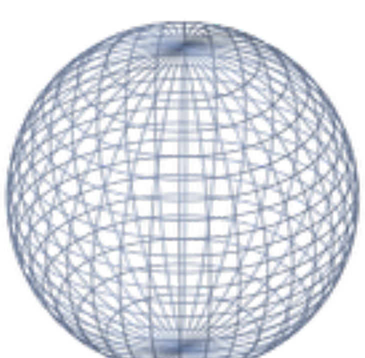
- Extra dimensions
- Gauge fields

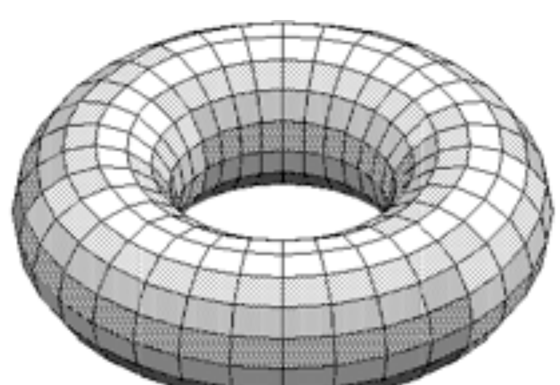
Elements of String Theory

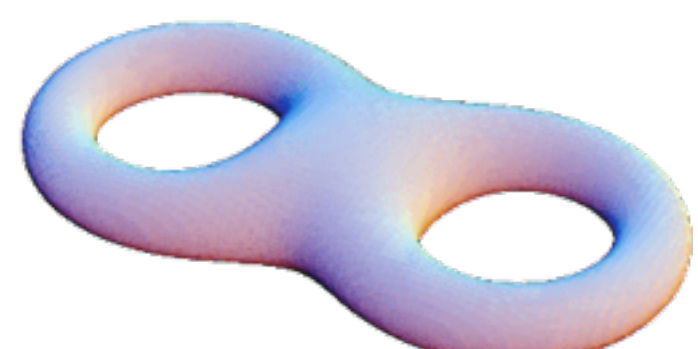
- Extra dimensions

- Gauge fields

- Topology

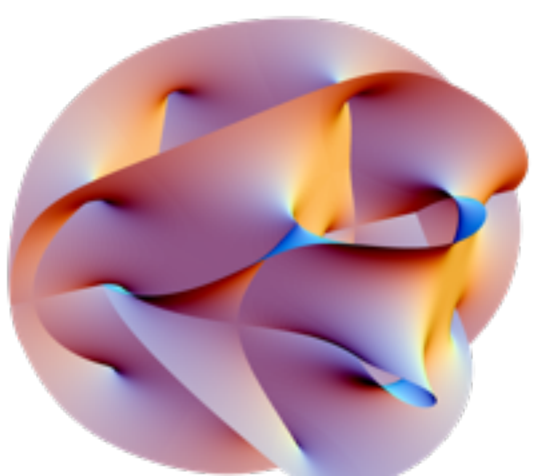






Elements of String Theory

- Extra dimensions
- Gauge fields
- Topology



Elements of String Theory

- Extra dimensions

- Gauge fields

- Topology

Give rise to a plenitude of Universes

Elements of String Theory

- Extra dimensions

- Gauge fields

- Topology

Give rise to a plenitude of massless particles in our Universe

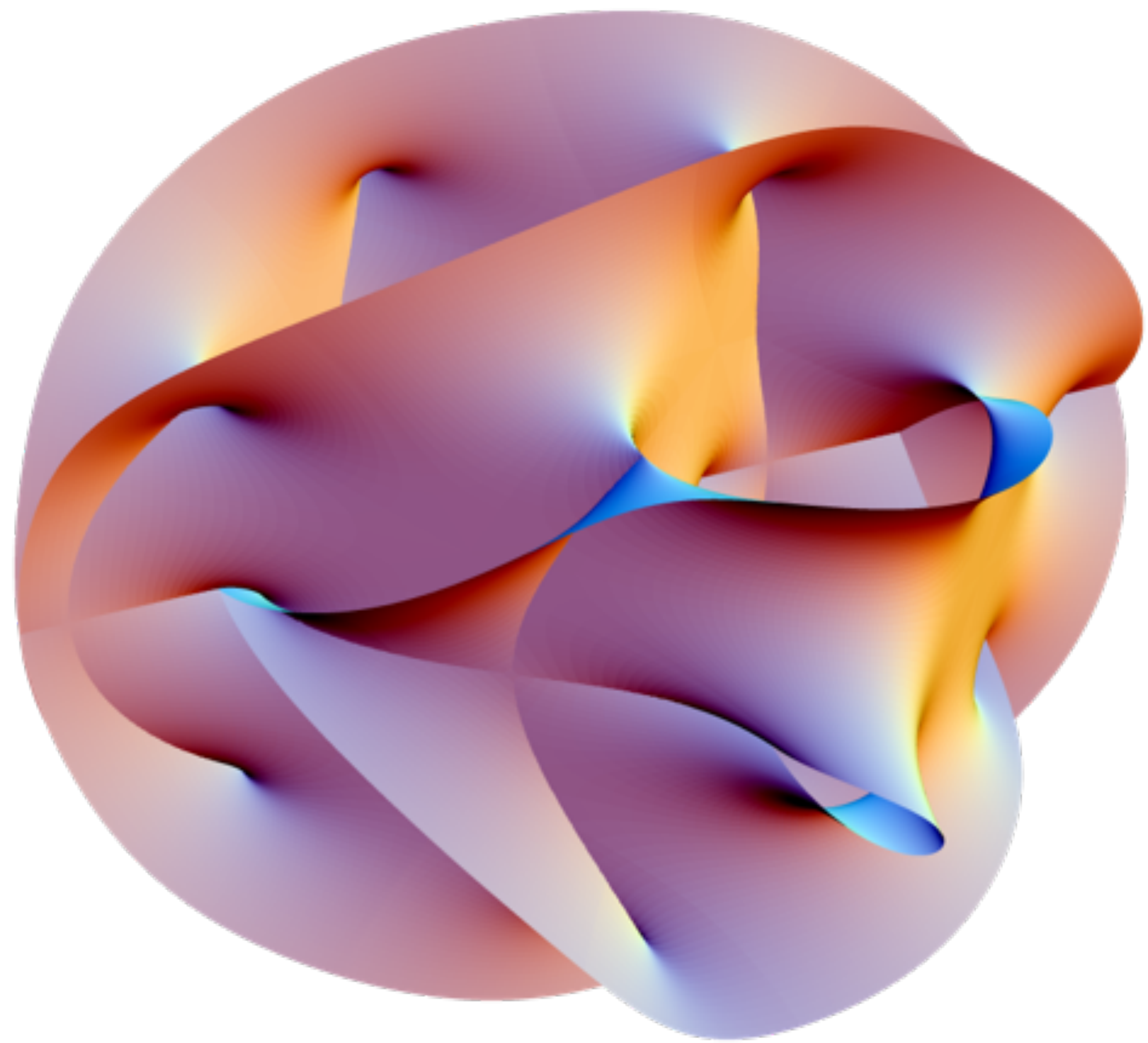
A Plenitude of Massless Particles

Compactification naturally gives rise to massless particles

In the presence of non-trivial topology,

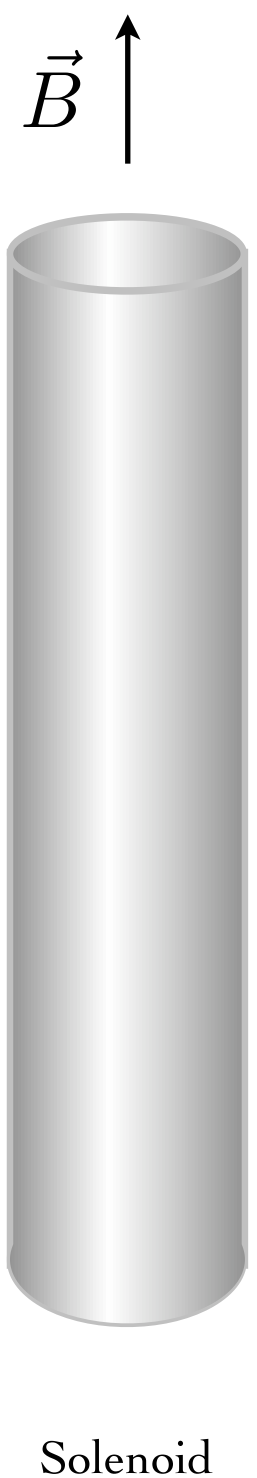
non-trivial gauge field configurations can carry no energy,

resulting in 4D massless particles



Non-trivial gauge configurations

The Aharonov-Bohm Effect



Taking an electron around the solenoid

$$e \int A_\mu dx^\mu = e \times \text{Magnetic Flux}$$

while

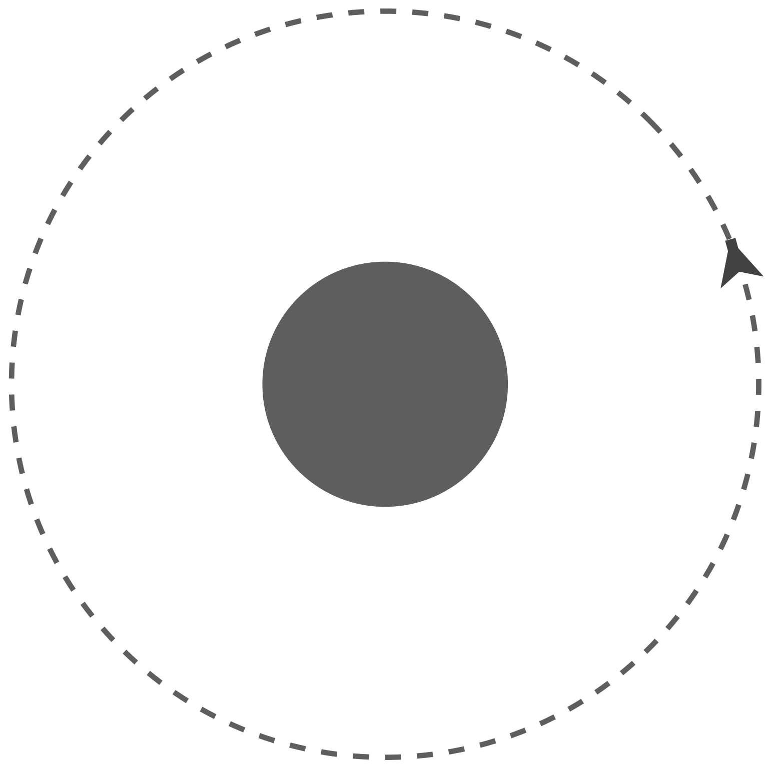
$$\vec{B} = 0$$

Energy stored only inside the solenoid

Non-trivial gauge configuration far away carries no energy

Non-trivial gauge configurations

The Aharonov-Bohm Effect



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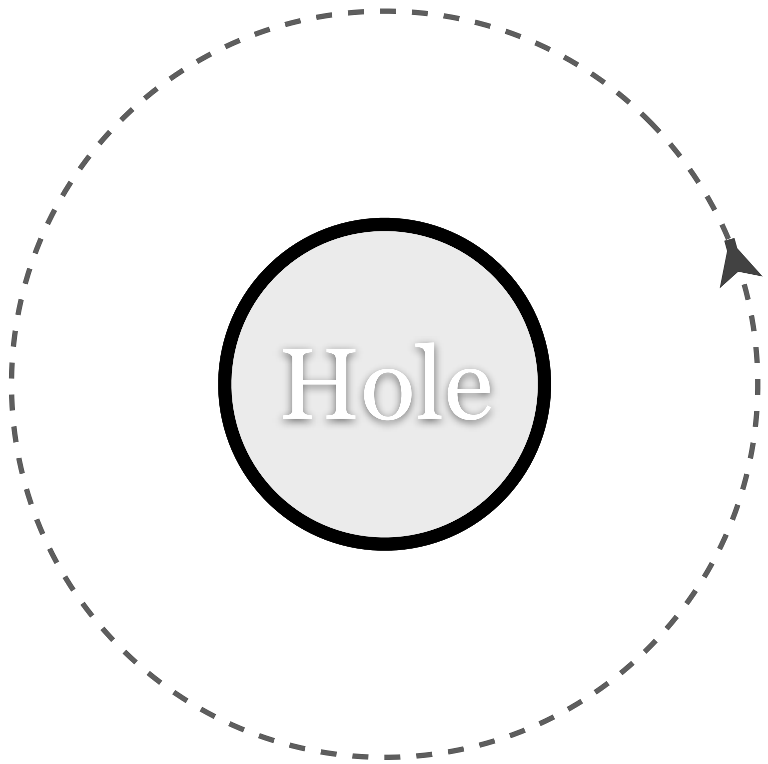

Taking an electron around the solenoid

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while

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Non-trivial topology:
"Blocking out" the core still leaves a non-trivial gauge, but no mass

A Plenitude of Massless Particles

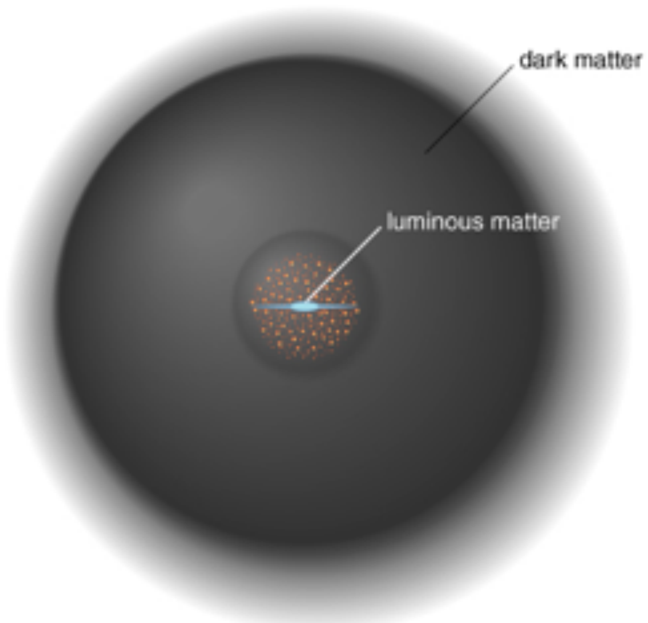
- Spin-0 non-trivial gauge field configurations: String Axiverse
- Spin-1 non-trivial gauge field configurations: String Photiverse
- Fields that determine the shape and size of extra dimensions as well as values of fundamental constants: Dilatons, Moduli, Radion

Properties of Plenitude of Particles from String Theory

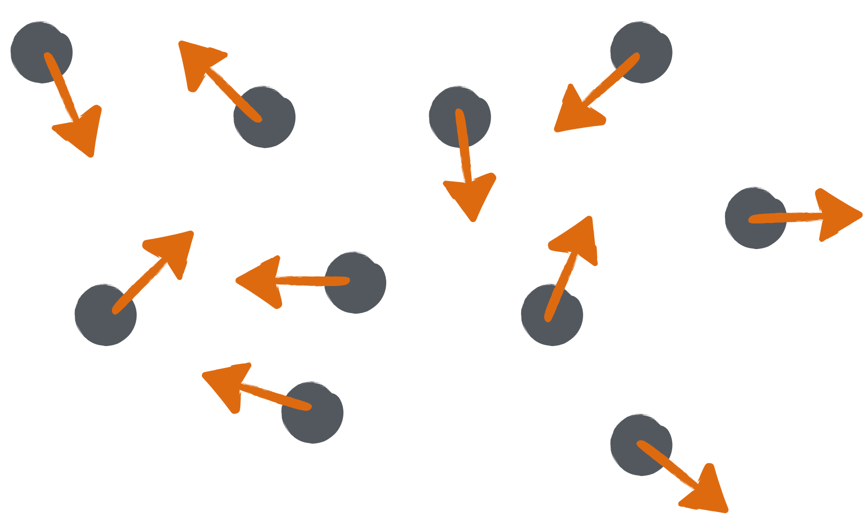
- They couple very weakly to the Standard Model
- They can be extremely light
- Constrained if the coupling is large enough by astrophysics, BBN, CMB…

What If DM Is a Boson and Very Light?

Dark Matter Particles in the Galaxy



Usually we think of …



like a WIMP

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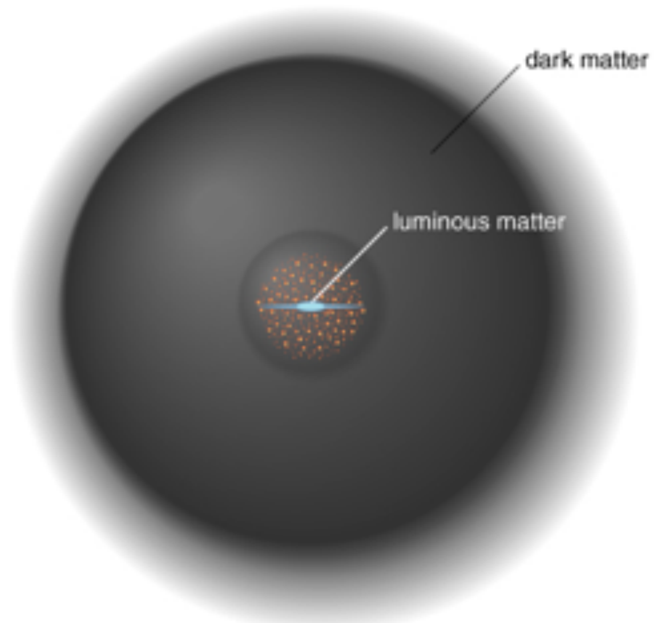

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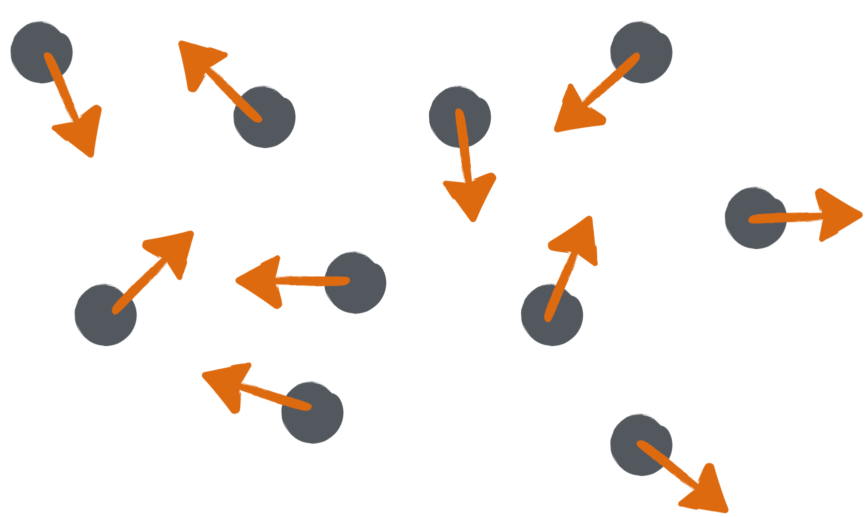

like a WIMP

instead of…

$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$

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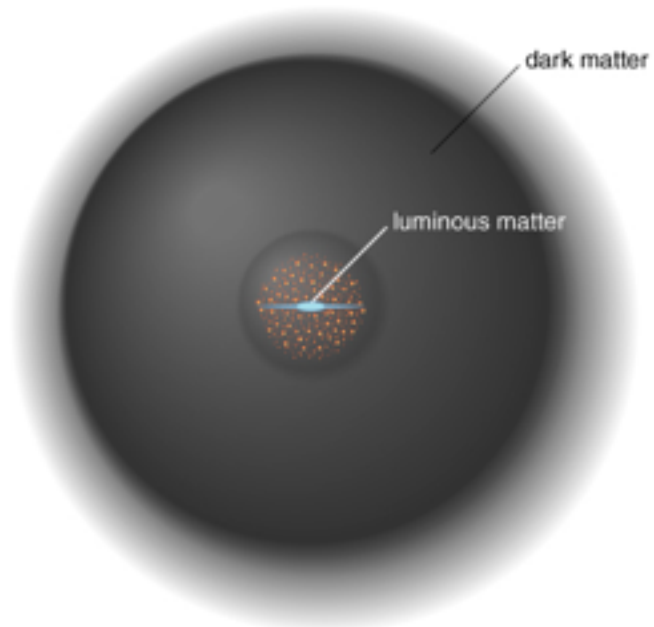

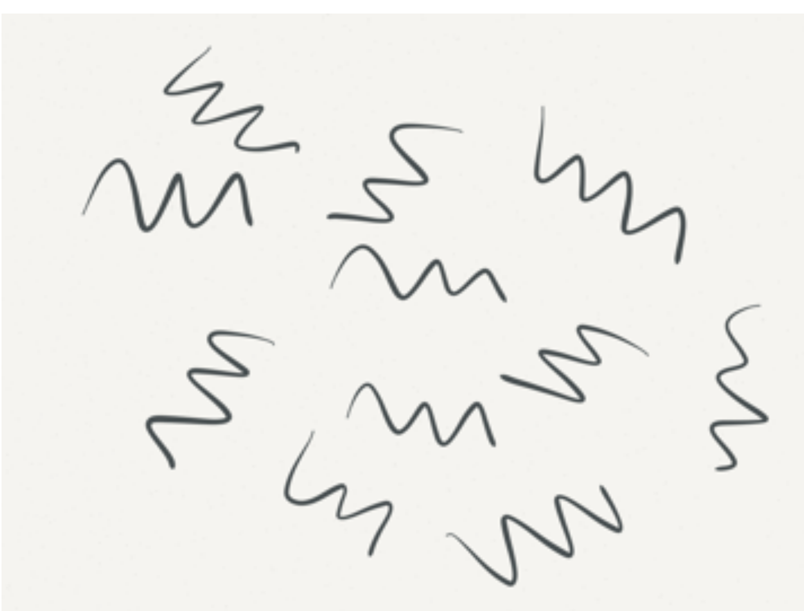

Decreasing DM Mass

$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$

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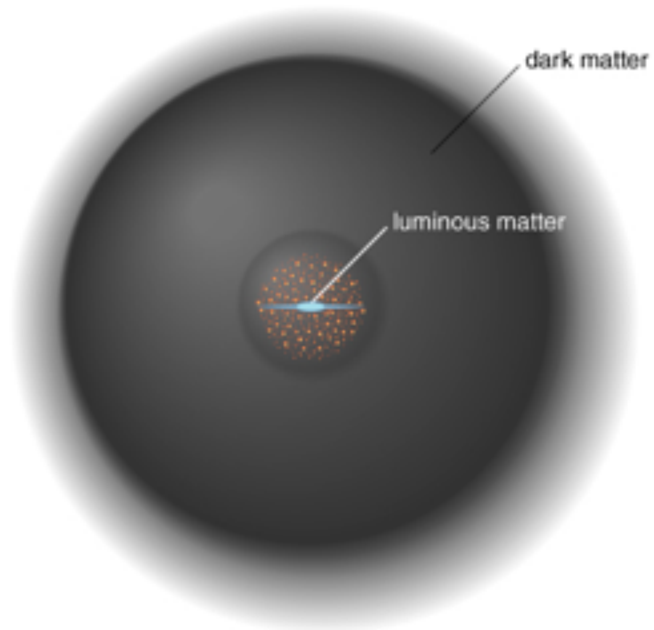
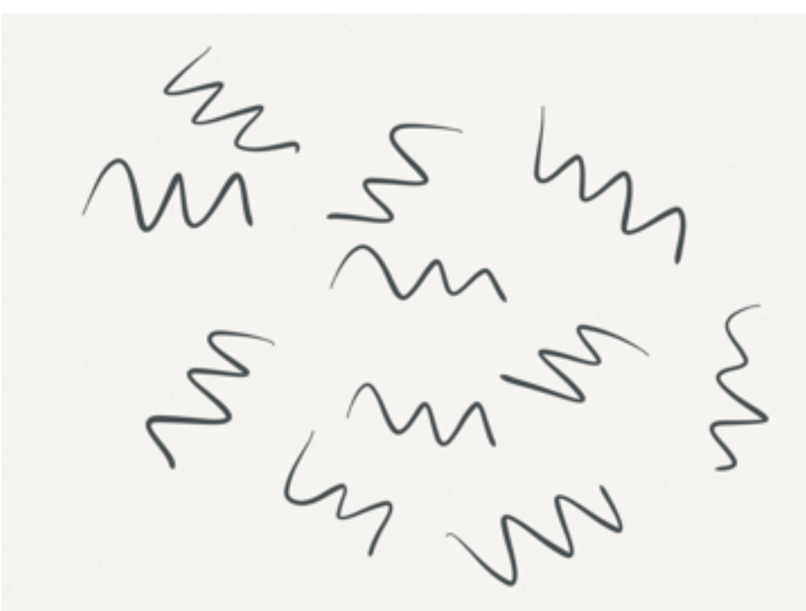




Decreasing DM Mass

$$\lambda_{DM} = \frac{\hbar}{m_{DM} v}$$

Equivalent to a Scalar wave

Going from DM particles to a DM "wave"

When $n_{DM} > \frac{1}{\lambda_{DM}^3}$

In our galaxy this happens when $m_{DM} < 1\ \mathrm{eV}/c^2$

we can talk about DM $\phi(x,t)$ and locally

$$\phi(t) \approx \phi_0 \cos \omega_{DM} t$$

with amplitude

$$\phi_0 \propto \frac{\sqrt{\text{DM density}}}{\text{DM mass}}$$

with frequency

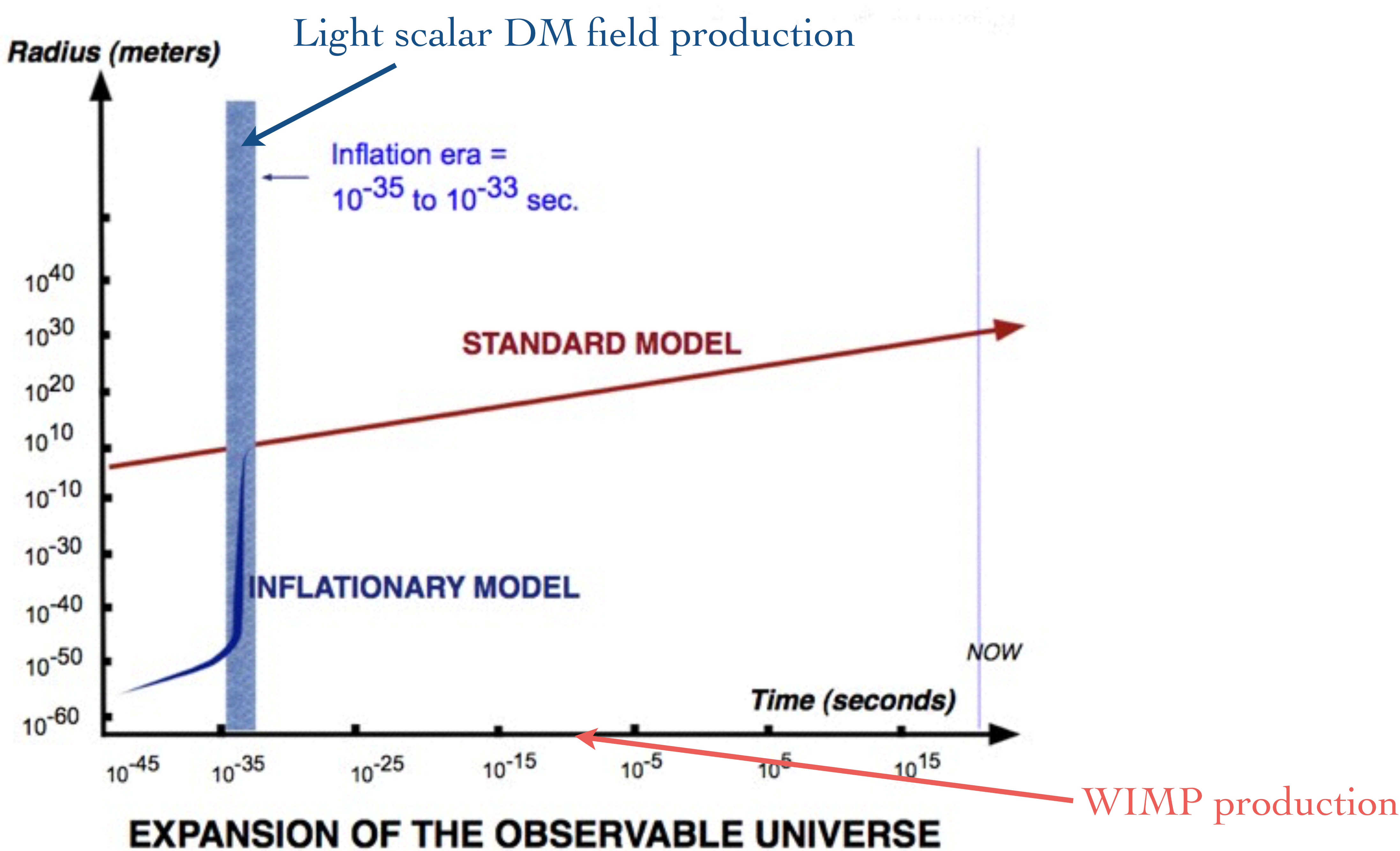
$$\omega_{DM} \approx \frac{m_{DM} c^2}{\hbar}$$

and finite coherence

$$\delta\omega_{DM} \approx \frac{m_{DM} v^2}{\hbar} = 10^{-6} \omega_{DM}$$

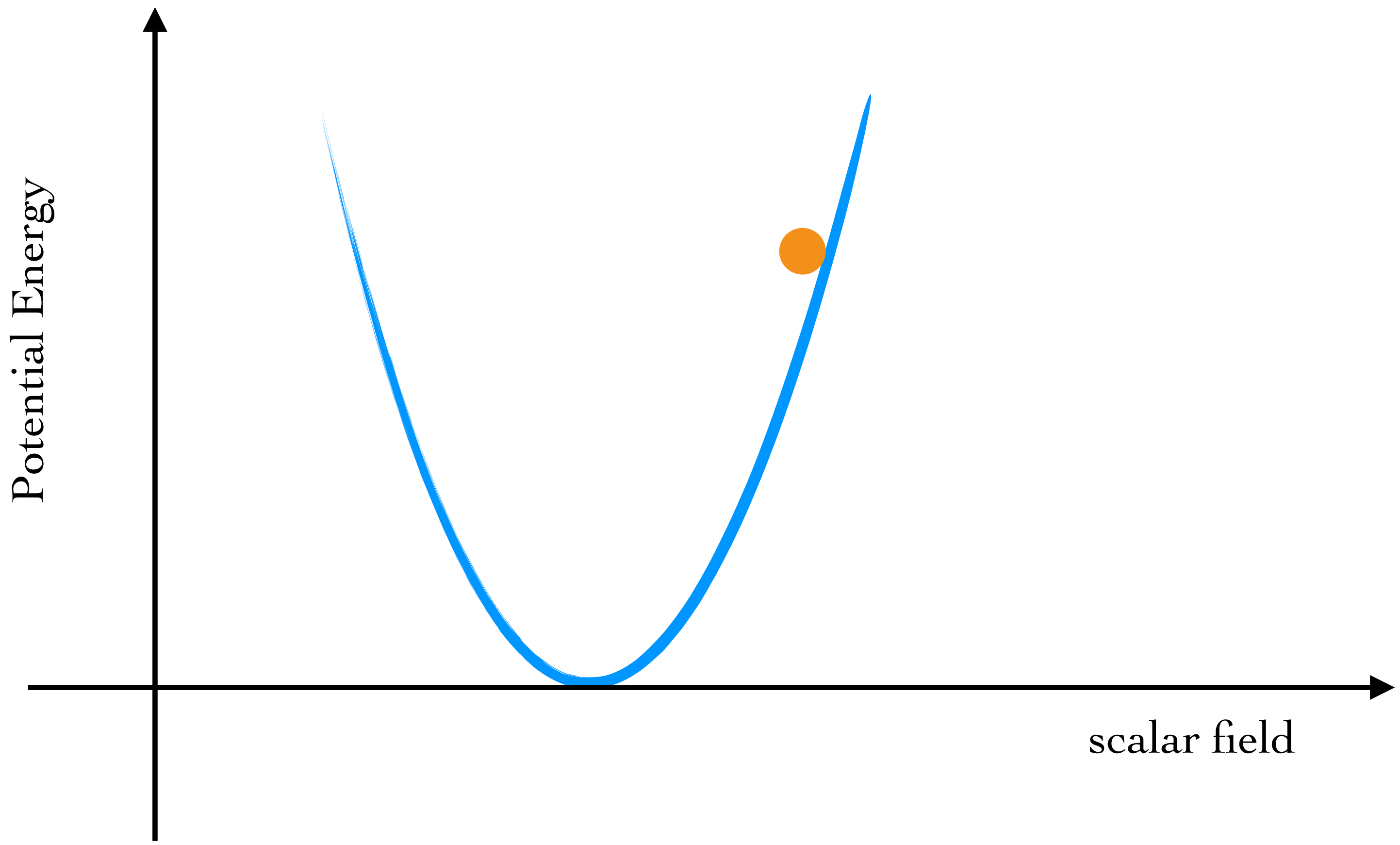
Scalar DM field Production Mechanism

- The "misalignment mechanism" during inflation



Light Scalar Dark Matter

- Produced by the misalignment mechanism



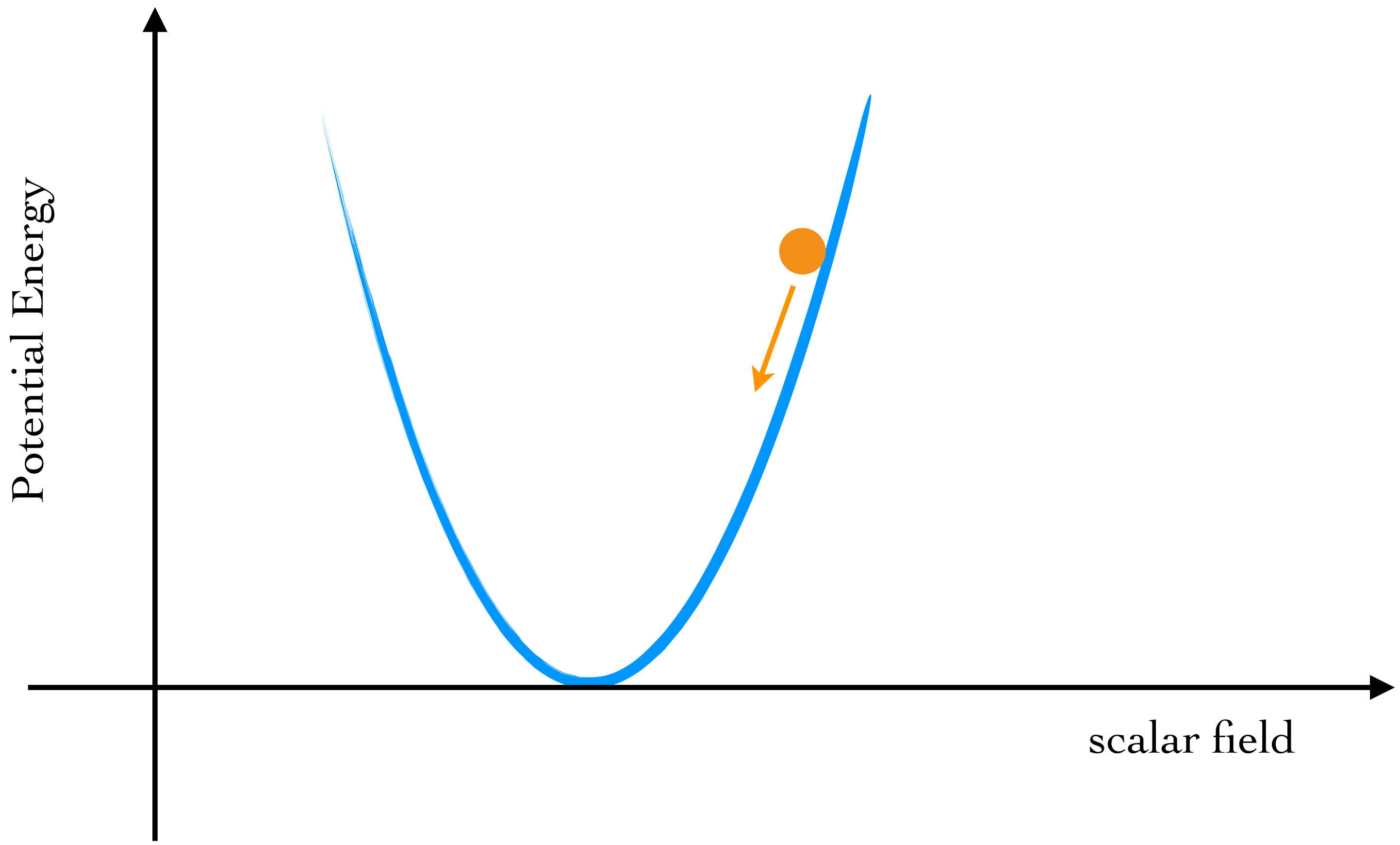
Frozen when:
Hubble > m_ϕ

Initial conditions set by inflation

*The story changes slightly if DM is a dark photon

Light Scalar Dark Matter

- Produced by the misalignment mechanism



Frozen when:
Hubble > m_ϕ

Oscillates when:
Hubble < m_ϕ

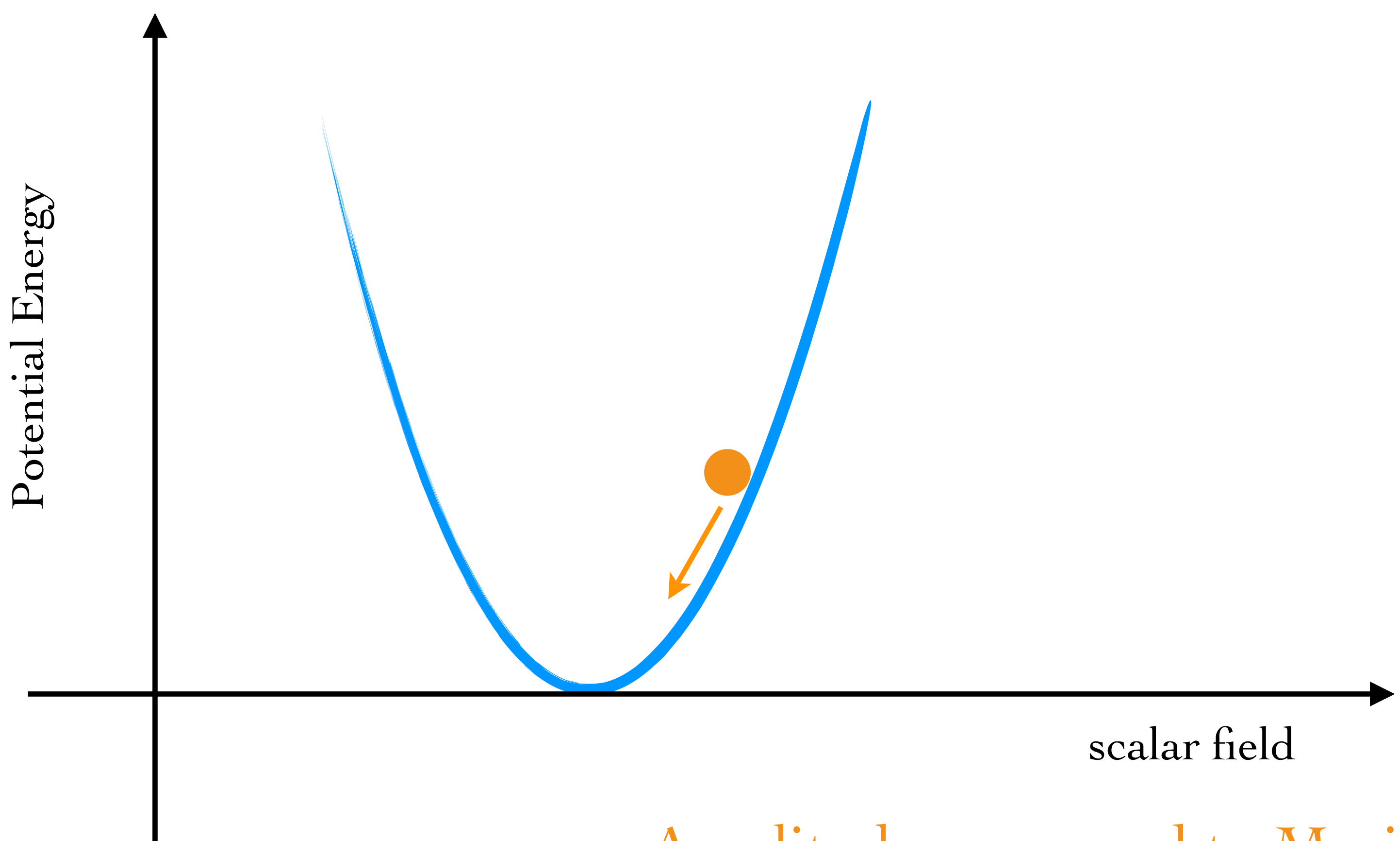
ρ_ϕ scales as a^{-3}
just like Dark Matter

Initial conditions set by inflation

*The story changes slightly if DM is a dark photon

Light Scalar Dark Matter Today

- If $m_\phi < 1$ eV, can still be thought of as a scalar field today



$m_\phi{}^2\ \phi_o{}^2\ \cos^2(m_\phi\, t) \sim \rho_\phi$

Coherent for $\upsilon_{vir}{}^{-2} \sim 10^6$ periods

Amplitude compared to M_{Pl} in the galaxy:

$$\kappa\phi_0 = \frac{\sqrt{8\pi\rho_\phi}}{m_\phi M_{\rm Pl}} = 6.4\cdot 10^{-13}\left(\frac{10^{-18}\,{\rm eV}}{m_\phi}\right)$$

Axion Dark Matter

- Axion wind (ex. CASPER, QUAX)

$$\mathcal{L} \supset \frac{\vec{\nabla}\phi}{f_\phi} \cdot \vec{\sigma} \qquad \text{just like detecting a} \qquad \vec{B}_{eff} \equiv \frac{\vec{\nabla}\phi}{\mu_f f_\phi}$$

- Axion-to-photon conversion (ex. ADMX)

$$B_\phi \sim g_{\phi\gamma\gamma}\phi B_{ext}$$

Dark Photon Dark Matter

- Abundance from inflation depends on H_I

P. W. Graham et al (2015)

$$\Omega_A = \Omega_{\rm cdm} \times \sqrt{\frac{m}{6 \times 10^{-6}\,{\rm eV}}} \left(\frac{H_I}{10^{14}\,{\rm GeV}}\right)^2$$

- Detected if kinetically mixed with the photon

$$\mathcal{L} \supset \epsilon F_{EM} F_{DM}$$

- Detected like a photon (ex. DM Radio)

$$\text{DM electric field} = \text{DM magnetic field} \sim \sqrt{\rho_{DM}}$$

Moduli Dark Matter

- Moduli set values of measured fundamental constants

- Couple non-derivatively to the Standard Model (as well axions with CP violation)

- Examples of couplings

$$\mathcal{L} = \mathcal{L}_{SM} + \sqrt{\hbar c}\frac{\phi}{\Lambda}\mathcal{O}_{SM}$$

$$\mathcal{O}_{SM} \equiv m_e e\bar{e},\ m_q q\bar{q},\ G_s^2,\ F_{EM}^2, \ldots$$

Fundamental constants are not really constants

Oscillating Fundamental Constants

AA, J. Juang, K. Van Tilburg (2014)

From the local oscillation of Dark Matter

Ex. for the electron mass:

$$d_{m_e}\sqrt{\hbar c}\frac{\phi}{M_{Pl}}m_e c^2 e\bar{e}$$

$M_{pl} = 10^{18}$ GeV
reduced Planck scale in energy

$$\frac{\delta m_e}{m_e} \approx \frac{d_{m_e}\phi_0}{M_{Pl}}\cos(\omega_{DM}t)$$

$$= 6.4 \times 10^{-13}\cos(\omega_{DM}t)\left(\frac{10^{-18}\ \mathrm{eV}}{m_{DM}c^2}\right)\left(\frac{d_{m_e}}{1}\right)$$

d_{me} : coupling strength relative to gravity

Fractional variation set by square root of DM abundance

Need an extremely sensitive probe…

Ultra-light Scalar Dark Matter

- Mediates new interactions in matter
  - Generates a fifth force in matter

  - Generates Equivalence Principle violation

Light Scalar Dark Matter Detection

- Atomic Clocks searches
- Resonant-Mass Detector searches
- Axion Force Experiments
- Detecting ultra-light particles with Astrophysical Black Holes

Oscillating Atomic and Nuclear Energy Splittings due to Dark Matter

- Optical Splittings

$$\Delta E_{\rm optical} \propto \alpha_{EM}^2 m_e \ \sim \text{eV}$$

- Hyperfine Splittings

$$\Delta E_{\rm hyperfine} \propto \Delta E_{\rm optical} \alpha_{EM}^2 \left(\frac{m_e}{m_p}\right) \sim 10^{-6}\ \text{eV}$$

- Nuclear Splittings

$$\Delta E\ (m_p,\ \alpha_s,\ \alpha_{EM}) \sim 1\ \text{MeV}$$

DM appears as a signature in atomic (or nuclear) clocks

Atomic Clocks

- Kept tuned to an atomic energy level splitting

Current definition of a second:
the duration of 9192631770 periods of the radiation
corresponding to the transition between the two hyperfine levels
of the ground state of the caesium 133 atom

- Have shown stability of 1 part in 10^{18}

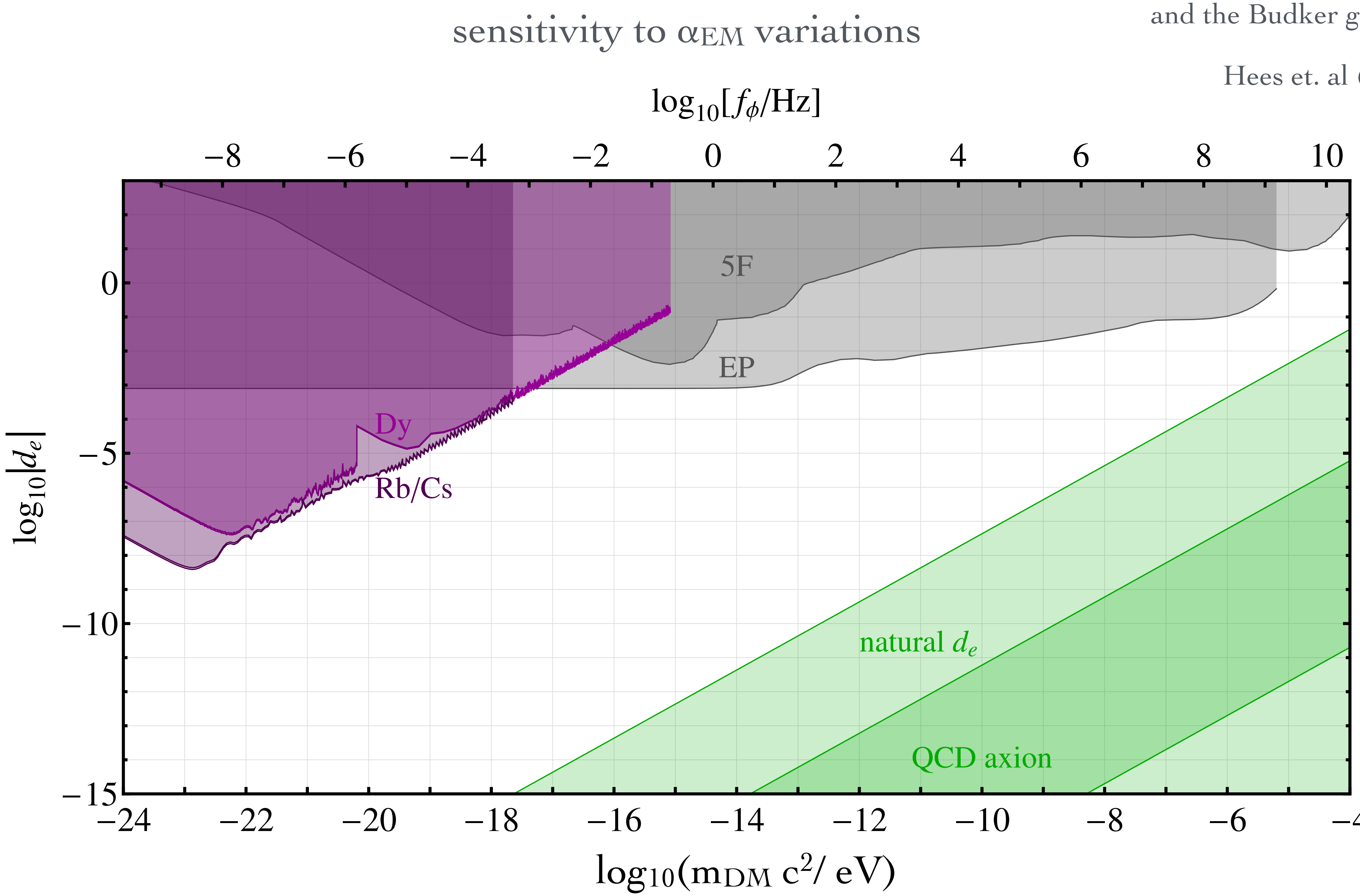
Compared to 1 part in 10^{13} expected by DM

- Have won several Nobel prizes in the past 20 years

The Dy isotope and Rb/Cs Clock Comparison

Ken Van Tilburg
and the Budker group (2015)

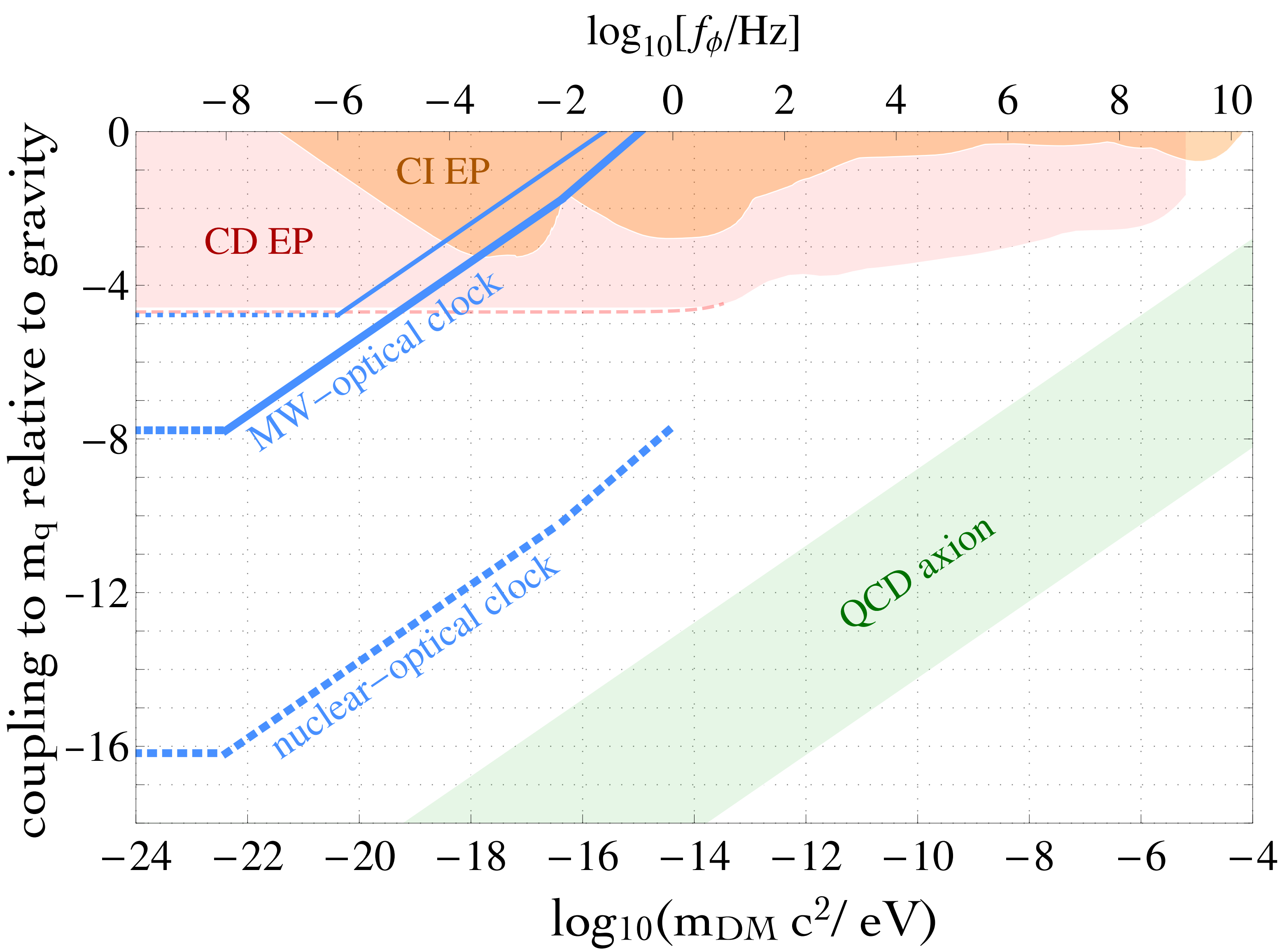
Hees et. al (2016)



Analysis performed with existing data

Nuclear to Optical Clock Comparison

Future Sensitivity of a ^{229}Th clock



Oscillating interatomic distances

- The Bohr radius changes with DM

  - $r_B \sim (\alpha\, m_e)^{-1}$

$$\frac{\delta r_B}{r_B} = -\left(\frac{\delta\alpha_{EM}}{\alpha_{EM}} + \frac{\delta m_e}{m_e}\right)$$

- The size of solids changes with DM

  - $L \sim N\,(\alpha\, m_e)^{-1}$

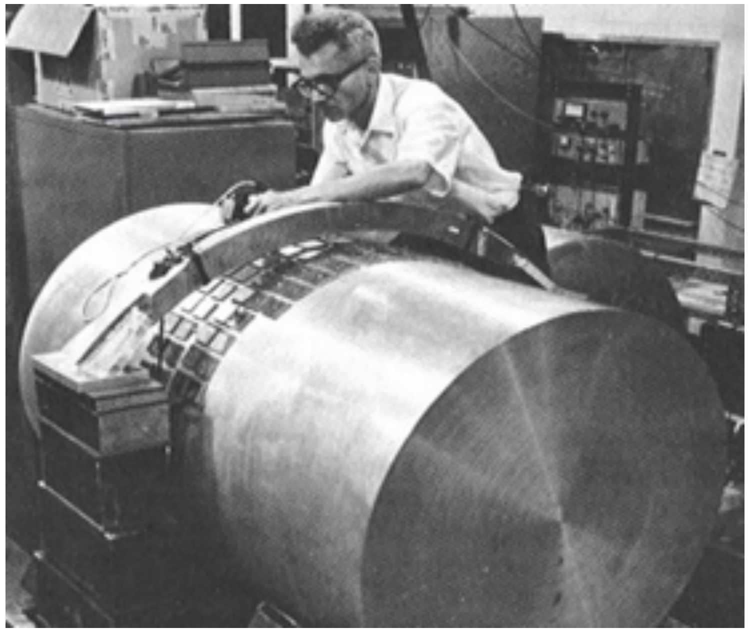
$$\frac{\delta L}{L} = -\left(\frac{\delta\alpha_{EM}}{\alpha_{EM}} + \frac{\delta m_e}{m_e}\right)$$

For a single atom $\delta r_B \sim 10^{-30}$ m

Need macroscopic objects to get a detectable signal

Resonant-Mass Detectors

- In the 1960's: The Weber Bar

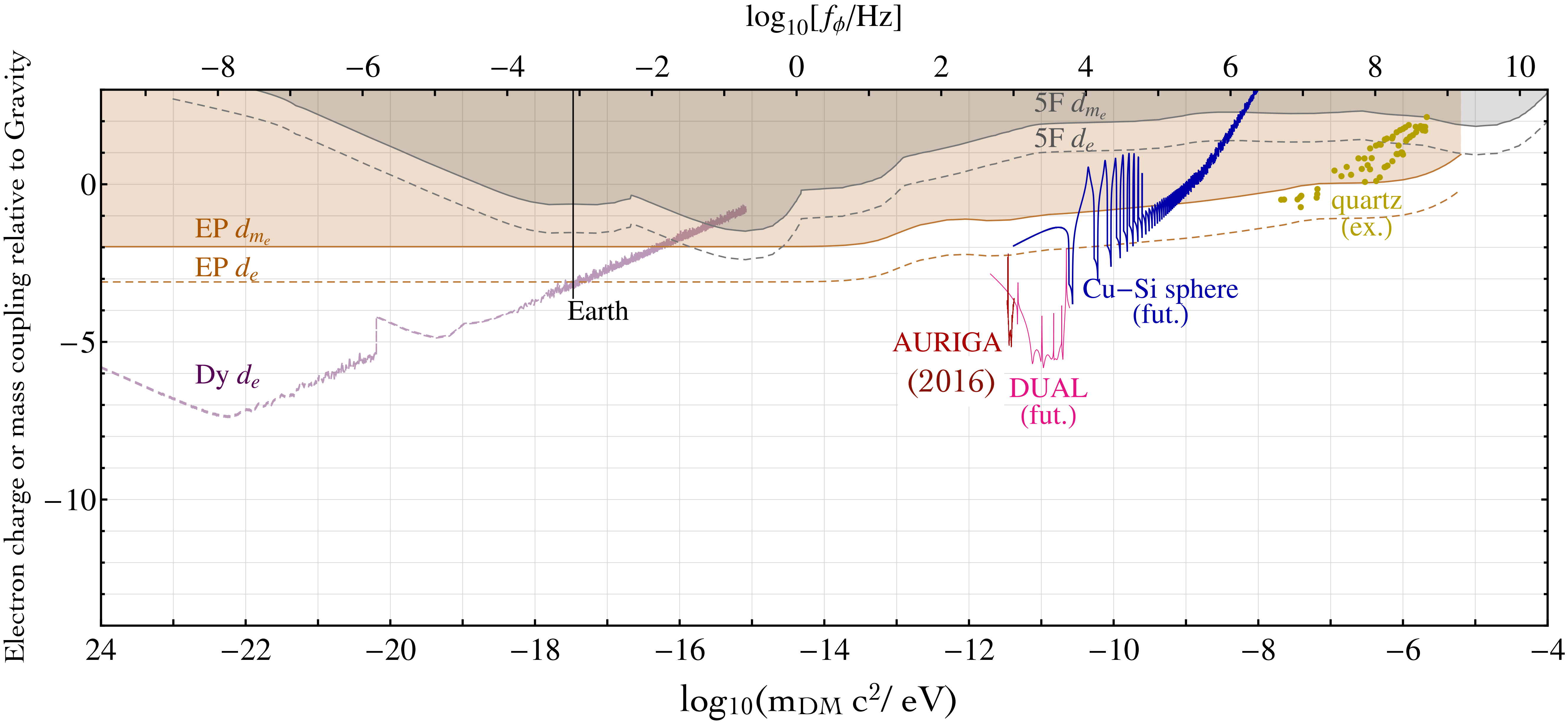


Fractional length variation $\delta L/L \sim 10^{-17}$

- Today: AURIGA, NAUTILUS, MiniGrail

Fractional length variation $\delta L/L \sim 10^{-23}$

What can be done in the future?

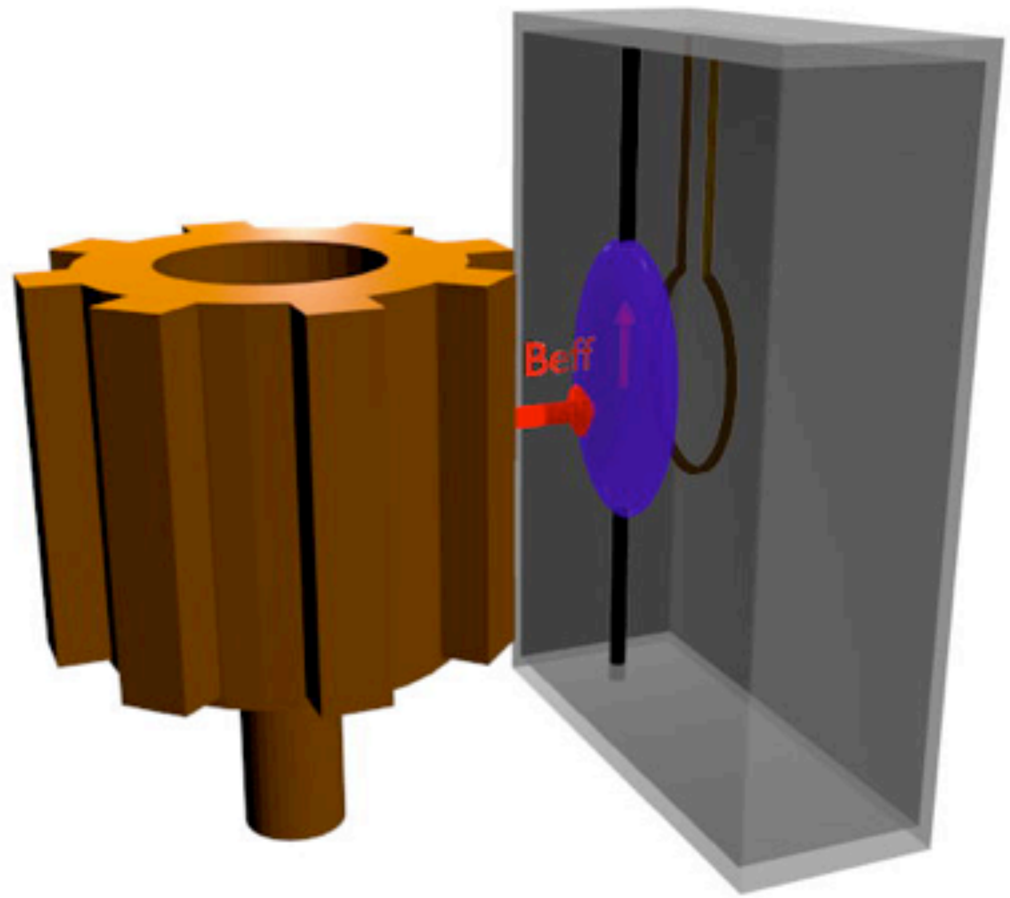


ARIADNE:

Axion Resonant InterAction DetectioN Experiment

with Andrew Geraci (2014)
and A. Kapitulnik, Chen-Yu Liu,J. Long, Y. Semertzidis, M. Snow (to be built)

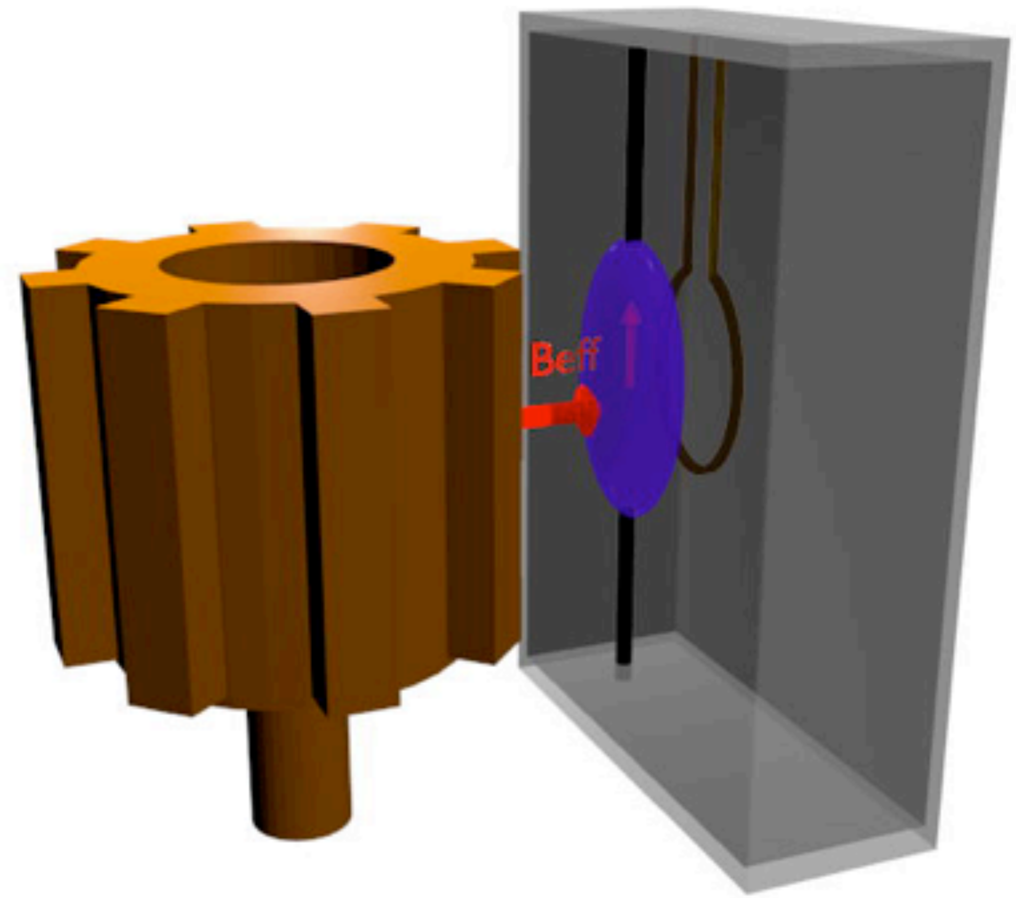
ARIADNE:
Axion Resonant InterAction DetectioN Experiment



He-3 NMR sample with T_2 up to ~1000 sec

ARIADNE:

Axion Resonant InterAction DetectioN Experiment



He-3 NMR sample with
T_2 up to ~1000 sec

$$B_{\rm min} \approx p^{-1}\sqrt{\frac{2\hbar b}{n_s \mu_{^3{\rm He}} \gamma V T_2}} = 3\times 10^{-19}\ {\rm T}\times$$
$$\left(\frac{1}{p}\right)\sqrt{\left(\frac{b}{1\ {\rm Hz}}\right)\left(\frac{1\ {\rm mm}^3}{V}\right)\left(\frac{10^{21}\ {\rm cm}^{-3}}{n_s}\right)\left(\frac{1000\ {\rm s}}{T_2}\right)}$$

$B_{min} = 10^{-16}\ T/(Hz)^{1/2}$
for SQUIDs

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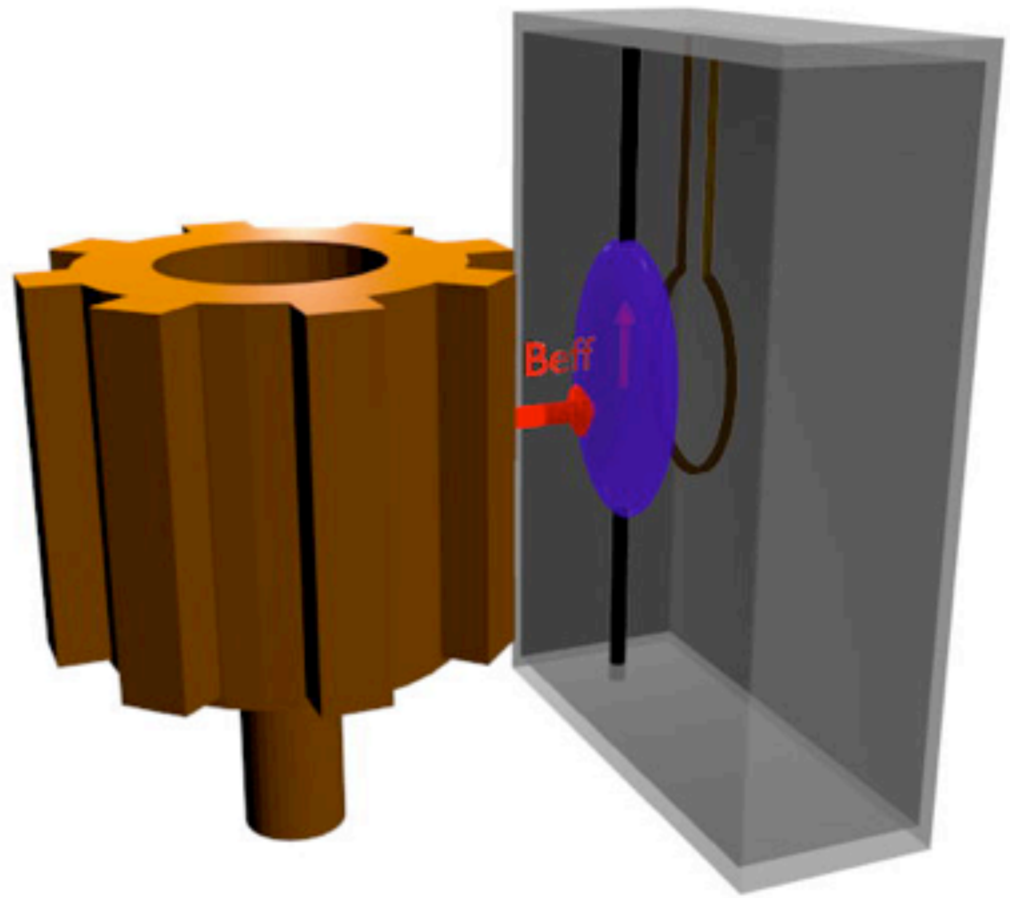

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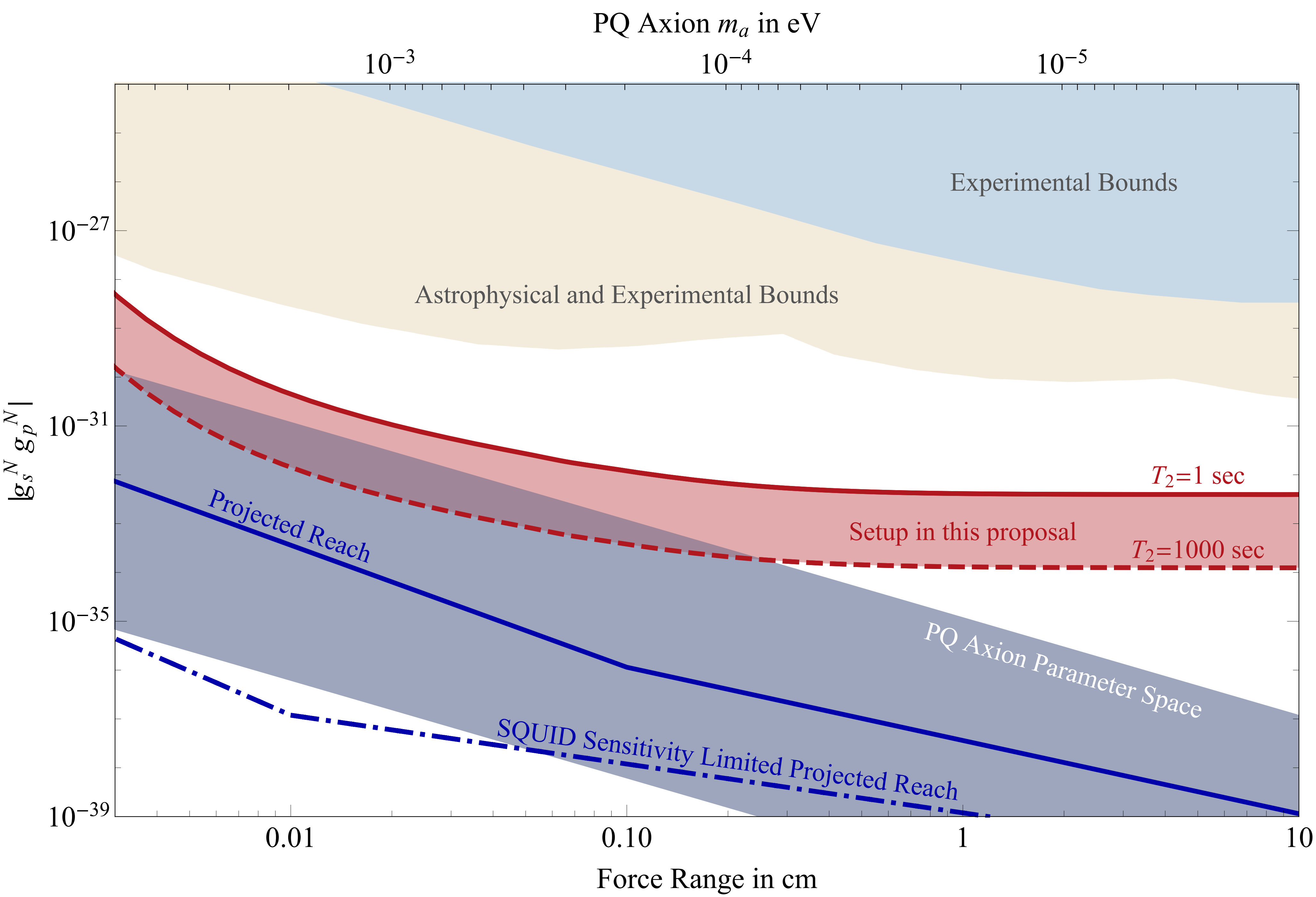
Monopole-Dipole Interaction Reach

Unpolarized Source Mass with 10^6 sec integration



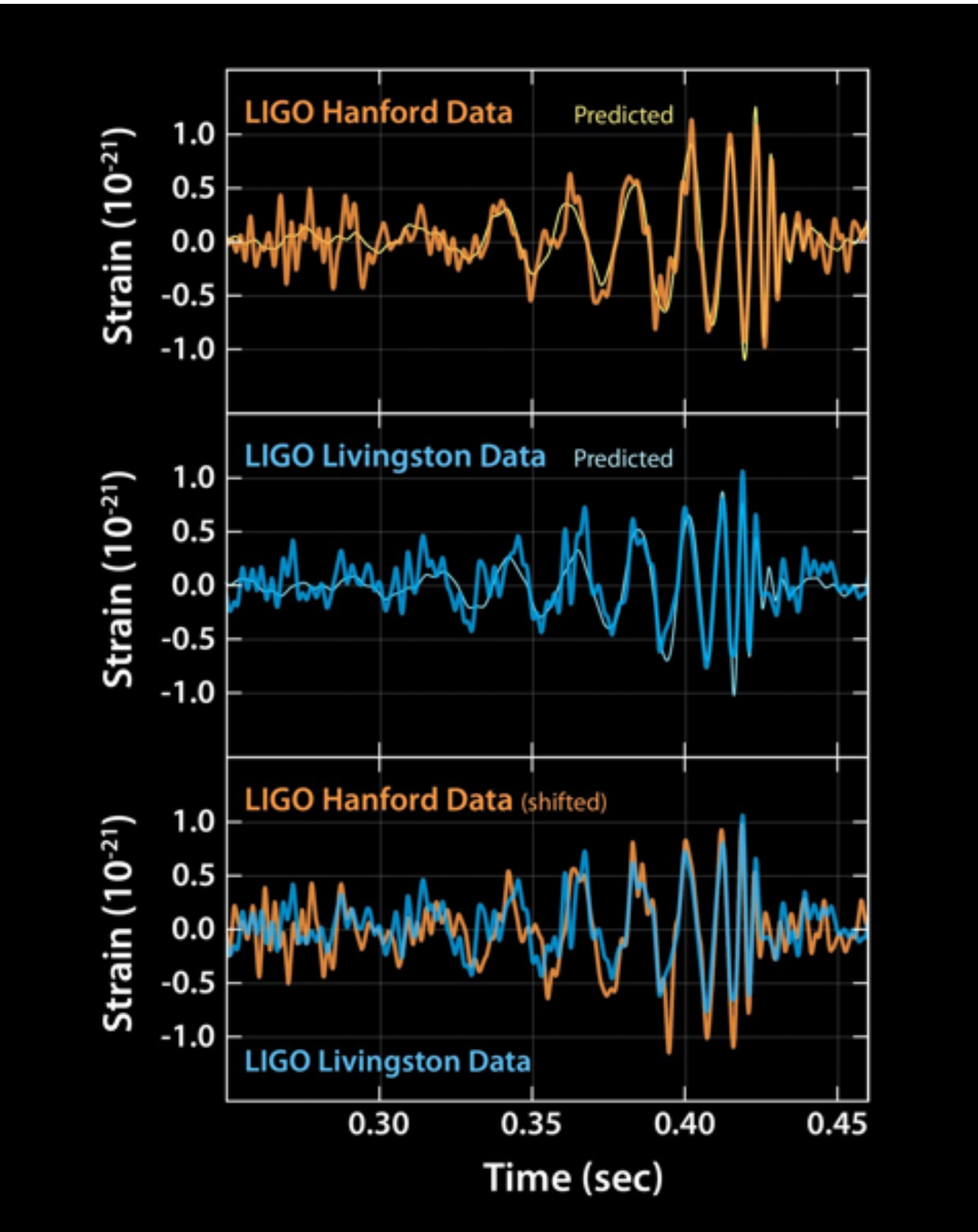
Projected Reach with increase of polarized spin density and larger NMR sample volume

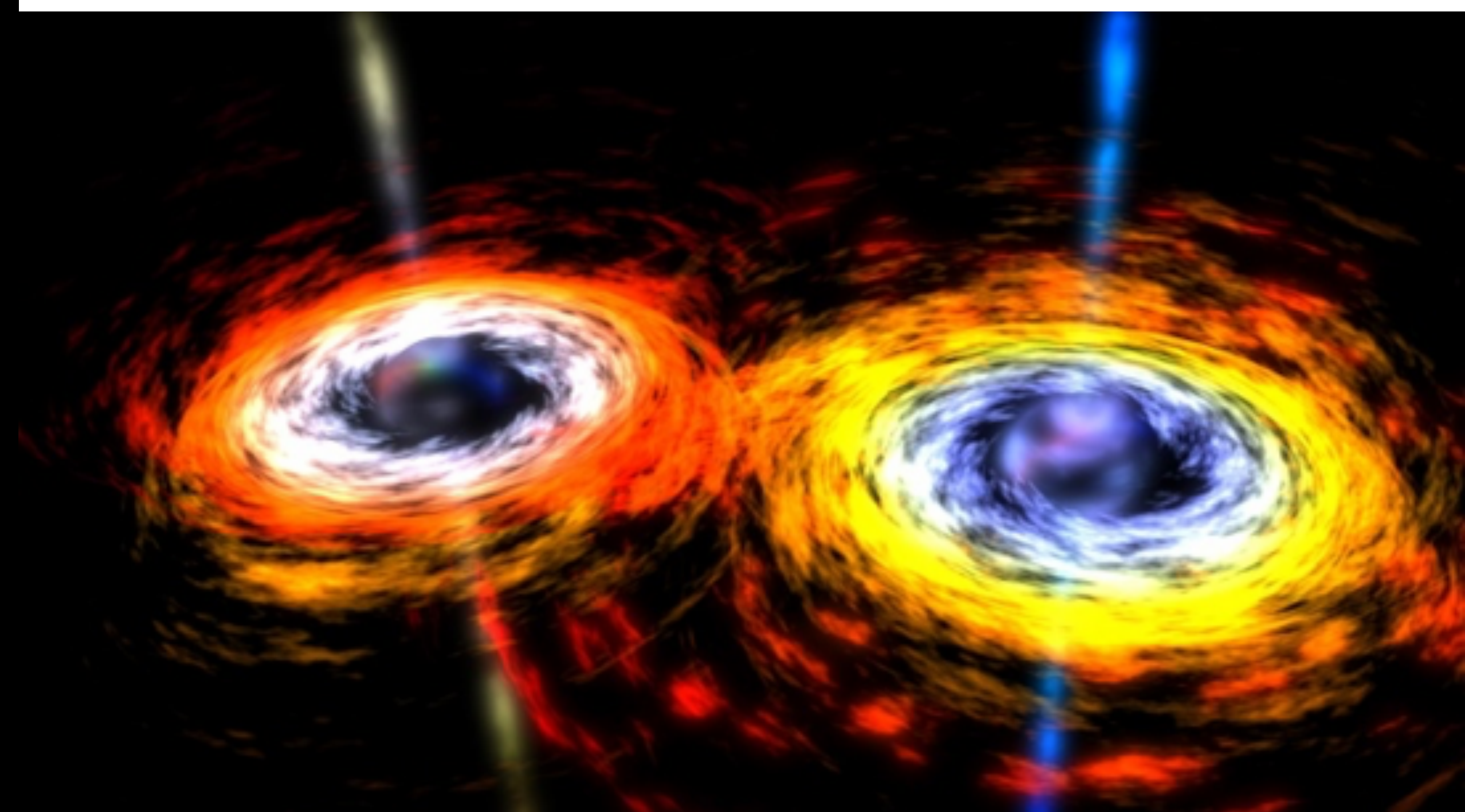
Black Holes as Nature's Detectors

1 km -10 billion km

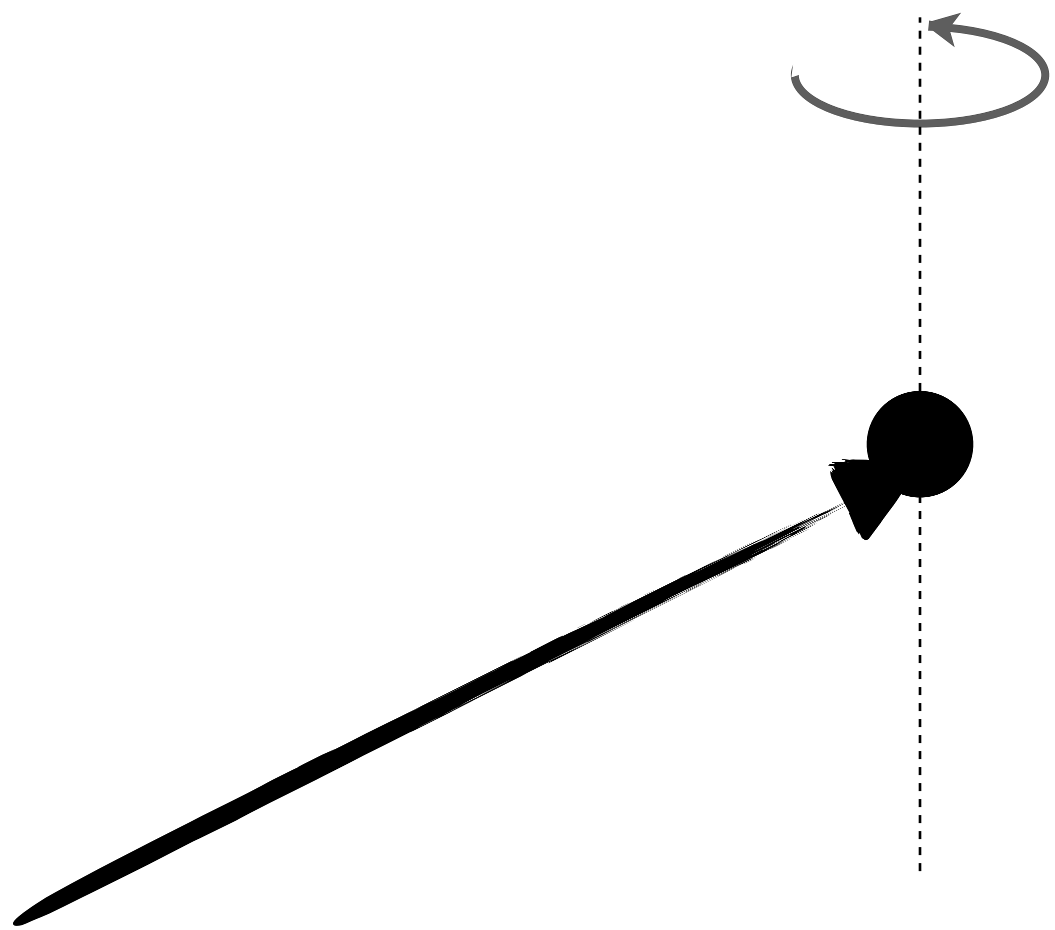
They can detect bosons of similar in size

September 14, 2015



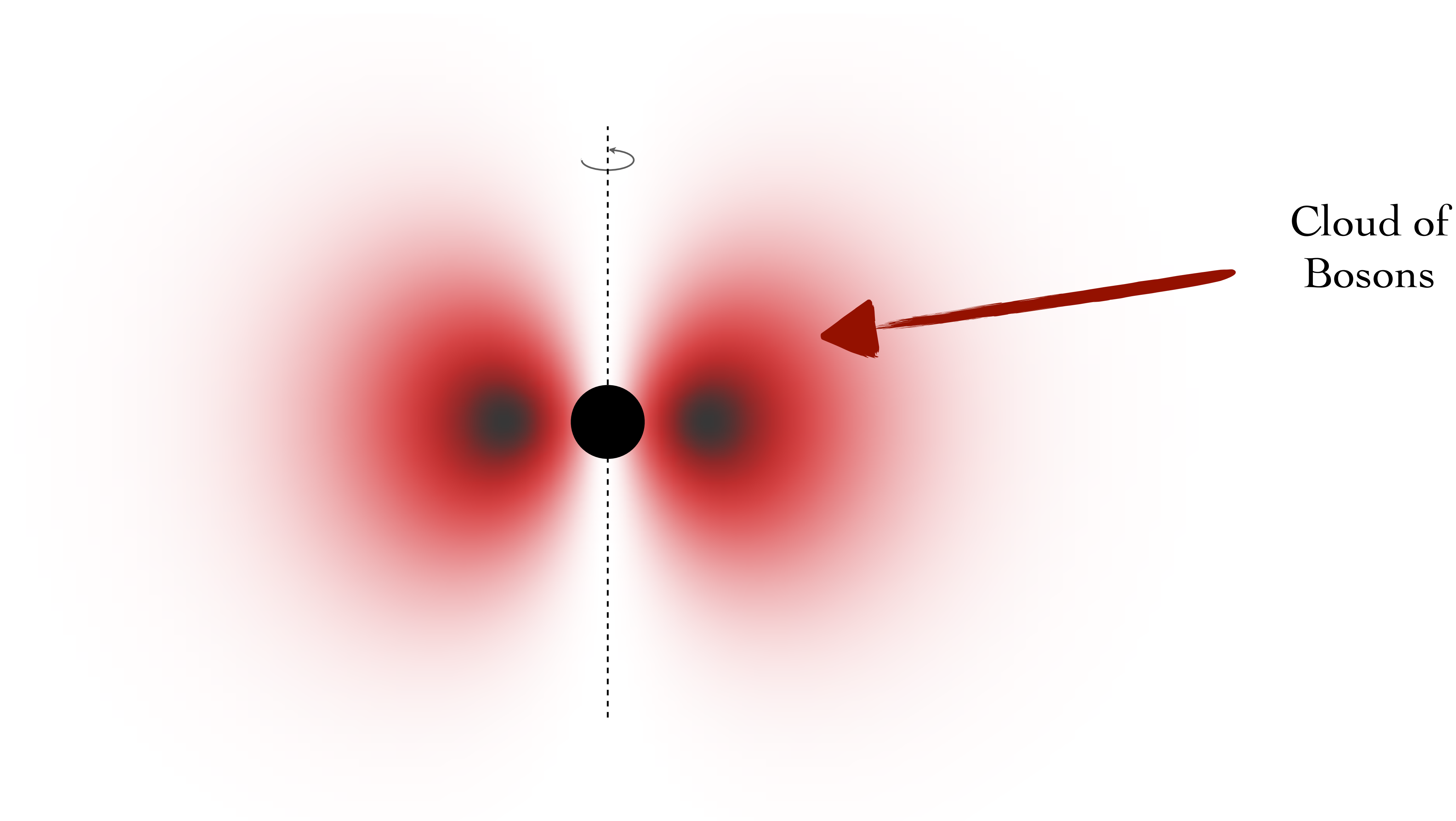


Superradiance and
The Gravitational Atom in the Sky



Rotating Black Hole

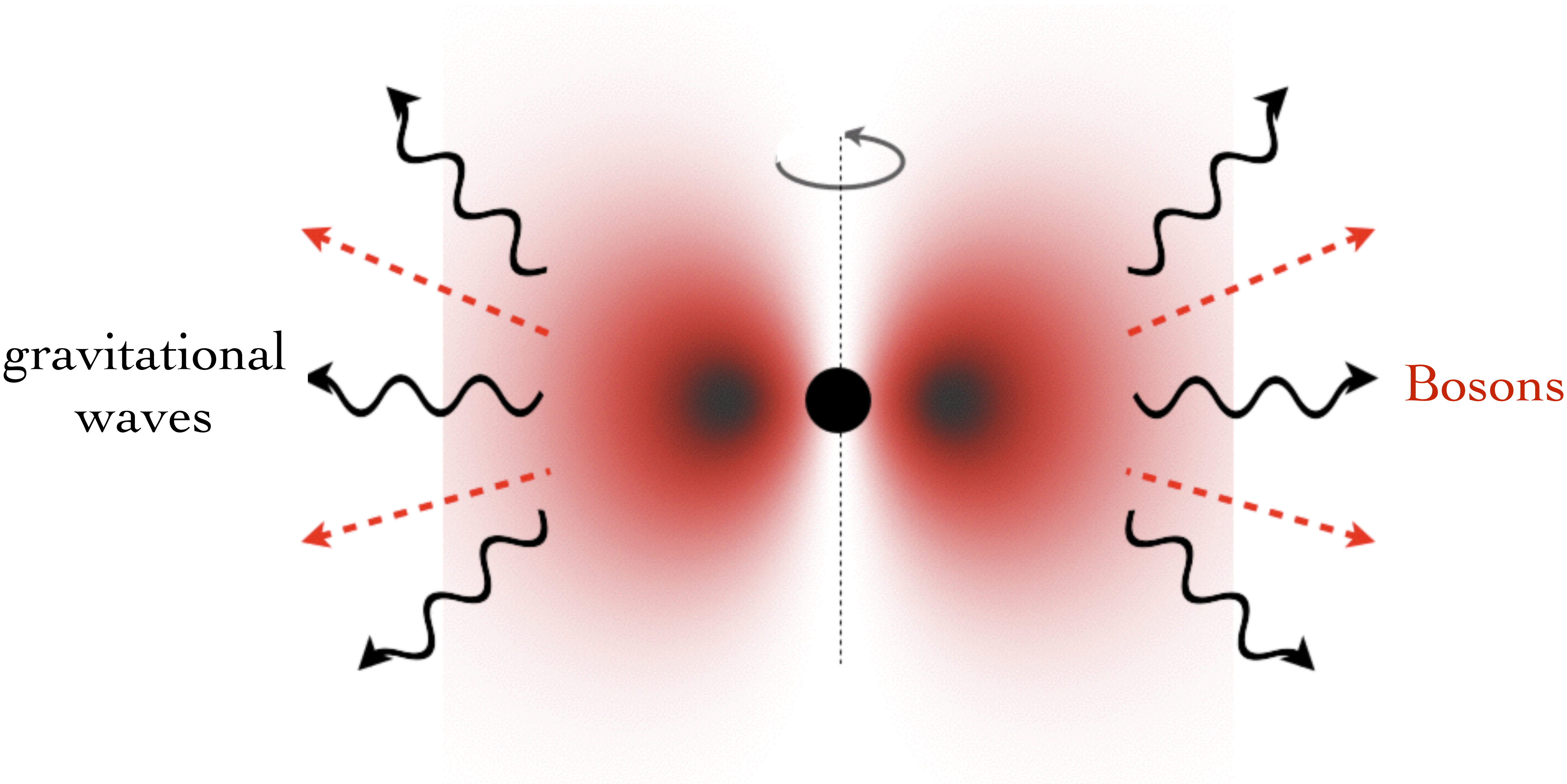
Superradiance and The Gravitational Atom in the Sky



Particles Occupying the Same Bound Orbit:

Can be comparable to the number of protons in all the stars in the universe

A Gravitational Wave Laser in The Sky



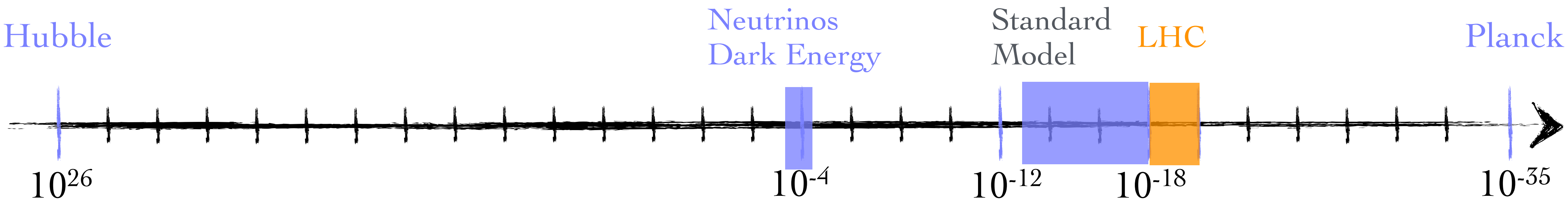
Summary

- There is excellent theoretical motivation for boson DM candidates below 1 eV in mass

- Correlated with observations across many experiments

This is only scratching the surface…

The Precision Frontier



Scale in meters

There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.
- Hamlet